# How smoke hinders escape from coal mine fires

F.N. Kissell and C.D. Litton

Abstract—*This study predicts the level of smoke that miners might meet while trying to escape a coal mine fire and describes how smoke would impede their safe escape. For this study, the authors assumed that miners exit through an escapeway adjacent to the burning entry, that some air would leak from the burning entry to the escapeway. The following conclusions were made:*

- *A very low amount of air leakage to the escapeway can produce a critical level of visual obscurity from smoke. This shows that intake airways may be as susceptible to smoke visibility problems as return airways.*
- *This critical level of smoke obscurity is reached much before a critical level of carbon monoxide is reached.*
- *Small fires can cause a severe sensory irritation that further limits vision. Thus, reliable eye protection is very important.*

*These results show that methods to guide miners through dense smoke will contribute greatly to saving lives during mine fires.*

## Intrsductisn

The aim of this research was to look at the role of smoke in hindering escape from coal mine fires, from either lack of visibility or sensory irritation. To do this, the authors forecasted smoke levels relative to fire size and carbon monoxide levels using data from conveyor belt test fires.

## Smake visibility and sensory irritation

### *Visibility*

For fires in buildings, various researchers have investigated the relationship between smoke density and visibility. Jin (1981) concluded the upper limit for adequate Visibility corresponds to an optical density of 0.06/m for persons unfamiliar and 0.2/m for persons who are familiar with the escape route. These equate to visibilities of 13 and 4 m (42 and 13 ft), respectively. Rasbash (1975) concluded the visibility limit is at a smoke optical density value of 0.08/m, corresponding to a 10-m (33-ft) visibility minimum. He determined visibility values using a black letter "C" on a white background. The test used focused headlamps held waist-high in a dark room while the subject wore a breathing apparatus.

Because of the short travel distance involved, Babrauskas (1979) used an optical density of 0.5/m as an obscurity criterion for escape from rooms containing burning furniture.

For fires in mines, Heyn (1977) measured the relation between smoke density and visibility in the Tremonia Experimental Mine in Germany, with similar results. In his tests, small conveyor belt fires resulted in visibilities of a few decimeters. Heyn also pointed out that water vapor condensation can make the smoke thicker.

### *Sensory irritants*

Smoke cloud irritants play a role in escape from fires. It is well known that smoke clouds contain a variety of sensory irritants that can make it impossible to see or breathe. For example, hydrochloric acid ($HCl$) is a common combustion product in coal mine conveyor belt fires. While not likely to be as lethal as carbon monoxide, it is a severe eye, nose and throat imtant. Purser (1988) reported that severe sensory irritancy occurs at an $HCl$ concentration of 100 ppm. Tewarson and Newman (1981) gave 50-100 ppm as the $HCl$ critical value for escape from fires. Research by Smith and Kuchta (1973) on burning belts showed that the production of $HCl$ averages about 12% of the $CO$ production.

Rasbash (1975) reviewed the impact of smoke cloud irritants. He indicated that eye irritation further decreased visibility. Also, lab workers used as subjects (Jin, 1981) reported that at the end of the test (optical density 0.2 to 0.3) the irritation and suffocation they experienced were about the most they could tolerate. Because of limited visibility in the test room, they could see only a small floor area around their feet. The smoke was from wood chips in an electric furnace. $CO$ levels had not reached 50 ppm.

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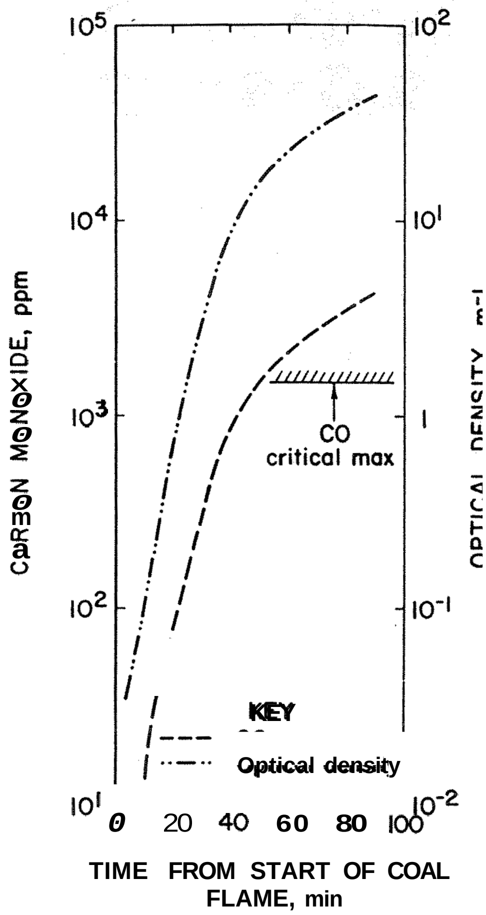


**Fig. 1—Downstream carbon monoxide and smoke density levels during the growth of a typical SBR belt/coal test fire.**

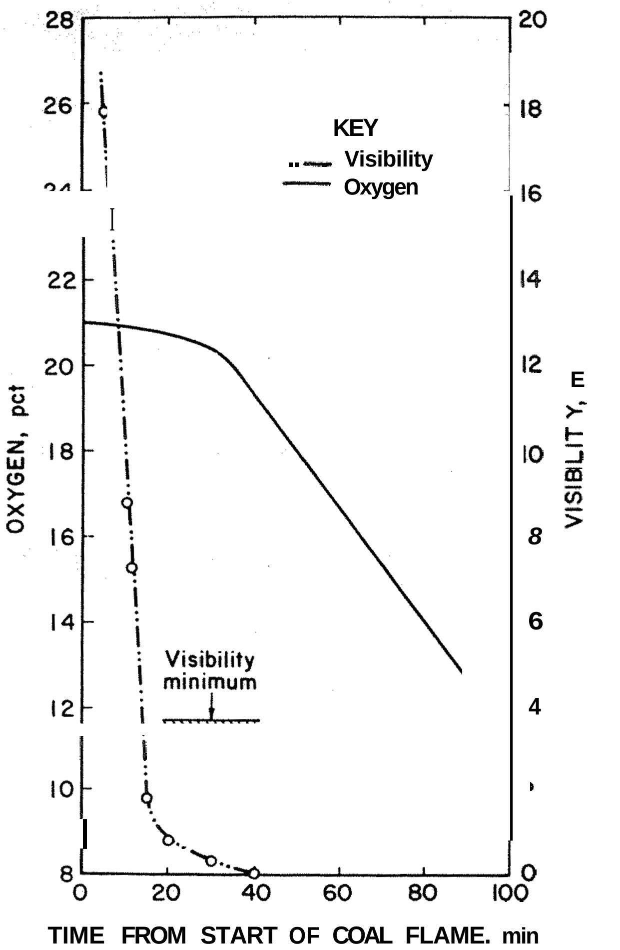


**Fig. 2—Downstream oxygen level and visibility during the growth of a typical SBR belt/coal test fire.**

## Smoke in a single entry

### Conveyor *belt fires*

For many years, the Bureau of Mines has conducted research in which various materials are burned to simulate a mine fire (Tewarson and Newman, 1981) (Lazzara and Perzak, 1990). Recently, Litton, Lazzara and Perzak (1991) studied the detection of conveyor belt fires. For these tests, they continuously measured fire products in the air as a pile of coal under the belt first smoldered, broke into flame, then set the belt on fire. These tests were in a tunnel that simulated a single mine entry.

Figures 1 and 2 illustrate the conditions 20 m (65 ft) downstream during the early growth stage of a typical test fire with styrene-butadiene rubber (SBR) belt. Time measures from the instant that flames erupt from the coal pile. The air velocity over the fire was 10m/sec (200 fpm) and the air quantity was 7.6 $m^3$/sec (16,000 cfm). The carbon monoxide and oxygen concentrations in the air were measured with infrared and electrochemical sensors. The smoke optical density was measured with a light intensity meter employing a prescribed light source and photoelectric cell. It is calculated as follows (Rasbash, 1975):

$$OD = (1/d)\text{Log}_{10}\,(I_0/I) \qquad (1)$$

where: OD = smoke optical density/m, d = length of light path in meters, $I_0$ = initial transmission on light path in clear air, and I = transmission on light path in smoke.

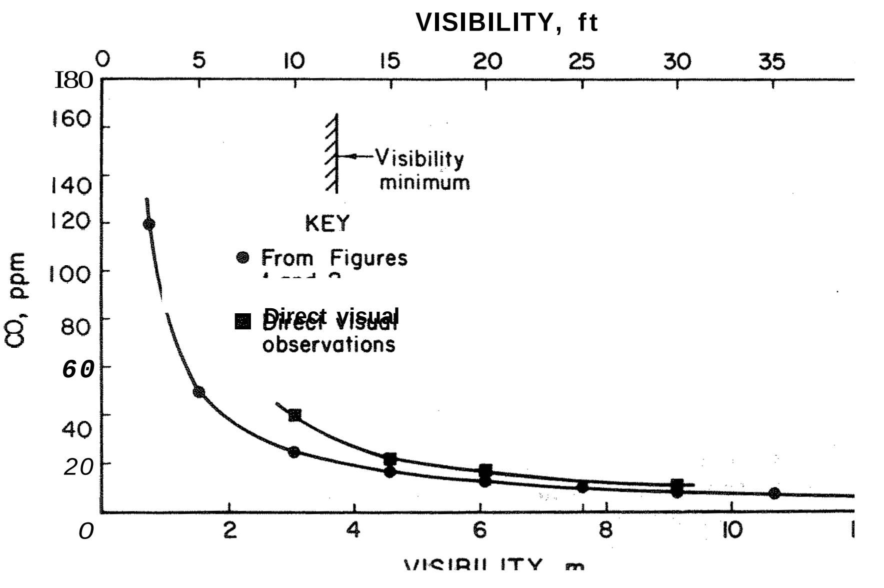


**Fig. 3—Downstream smoke visibility and carbon monoxide levels during the growth of a** typical **SBR belt/coal test fire.**

Note that the trend of the curves in Fig. 1 indicates that the CO/OD ratio does not vary much over the entire 90 min. At 10 min, the ratio is 120 ppm x m. At 90 min, it is 93 ppm x m.

### *Calculating visibility*

Values for visibility, or how far an individual can see in the smoke, can be calculated from the optical density. The relation between the two can be derived in the following manner:

According to Rasbash (1975), an optical density value of 0.08 corresponds to a 10 m (33 ft) visibility. Assume a test in which measurements are conducted with a smoke density meter, and the path length over which measurements are made is 10 m (33 ft). Assume the smoke density during the test is such that an optical density of 0.08 is computed, or $0.08 = (1/10)\log(I_0/I)$. From this, $\log(I_0/I) = 0.8$

In accordance with Rasbash (1975), visual observations during the test indicated that the visibility limit was 10 m (33 ft). Thus, given a path d, where the smoke level is such that $\log(I_0/I)$ is equal to 0.8, then d is the visibility.

It follows generally that $OD = (1/d)(0.8)$. So, if the optical density is known, the visibility can be calculated. The calculated Visibility values at various fire times are shown in Fig. 2, and the direct relationship between CO and visibility, using the information in Figs. 1 and 2, is in Fig. 3.

### *Direct visual observations on videotape*

The visibility values in Figure 3 correspond to surprisingly low CO values. Therefore, to gain visual proof of this information, the authors conducted a small test fire with 91 kg (200 lb) of coal and 0.28 $m^2$ (3 sq ft) of belt in a 2.1- x 5.4-m (7- x 18-ft) entry of the Experimental Mine at the Bureau's Lake Lynn Laboratory.

Downwind of the fire in the same entry at a distance of 270 m (900 ft), a video camera was set up with a single light next to it. Three cardboard signs were placed at 3, 6 and 9 m (10, 20 and 30 ft) from the camera, as well as a mannequin 4.5 m (15 ft) from the camera. The signs showed the distance in 267 mm (10.5 in.) black letters on a white background. This is similar to the approach used by Rasbash (1975) for visibility experiments. Near the signs, the CO concentration was measured at the roof and halfway up one rib. As the fire grew, the CO concentration was noted at the time each of the signs and the mannequin disappeared from view as the smoke grew thicker. The CO data and the video camera showed no stratification, although close to the fire there was a thick smoke layer at the roof with clear air underneath. Traveling 270 m (900 ft) was enough to mix the smoke and CO evenly into the airstream. The results are shown in Fig. 3 as "direct visual observations."

For example, the 9 m (30 ft) sign disappeared at an average CO concentration of 10.4 ppm, the 6 m (20 ft) sign at 17.7 ppm, etc. The resulting curve confirms well the visibility and CO vs. time values from Figs. 1 and 2.

### *Analysis of the single airway data*

Tewarson and Newman (1981) gave some tentative critical values of various fire contaminants that affect escape from mines. For visual obscurity in smoke, their critical optical density value is 0.218/m. This equates to a 3.7-m (12-ft) acceptable visibility minimum. For CO, their critical maximum

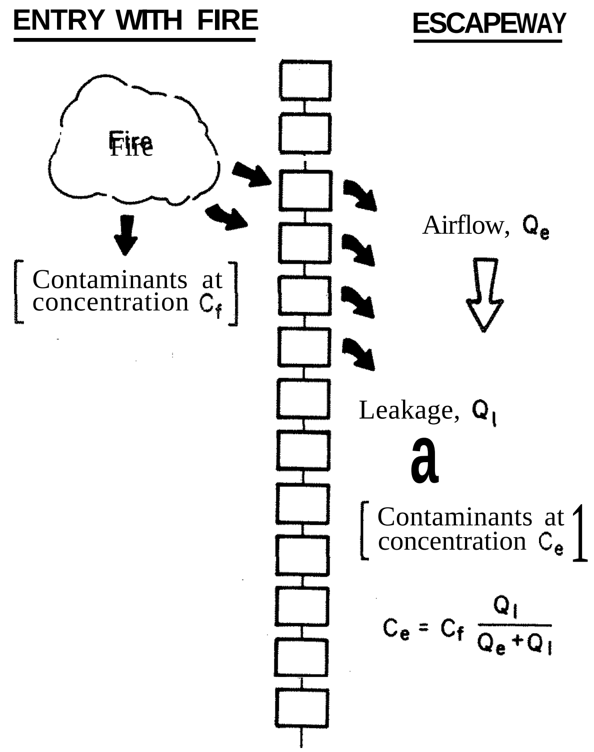


Fig. 4—Entry with fire and adjacent escapeway.

value is 1500 ppm. For the test fire illustrated in Figs. 1 and 2, the smoke density reaches the minimum acceptable visibility at 13 min. At this 13 min point, the CO level was 24 ppm. Mitchell (1990) gave a rule of thumb that the burning of 0.45 kg (1 lb) of coal yields 0.014 $m^3$ (1/2 cu ft) of CO. This allows CO to be used as an indicator of fire size for an equivalent coal fire. Given an airflow of 7.5 $m^3$/sec (16,000 cfm), the burning rate of an equivalent coal fire at 13 min was 0.36 kg/min (0.8 lbs per min). As the fire grew, the critical maximum CO value of 1500 ppm was reached at 51 min. At this point, the calculated burning rate of an equivalent coal fire was 22 kg/min (48 lbs per min), or 60 times greater.

In summary, small fires in their early growth stage can produce minimum smoke visibility levels.

## Smoke in the adjacent escapeway

Only miners escaping through the entry on fire would experience the contaminant levels shown in Figs. 1 and 2. It is more likely that miners would choose to escape through an entry that was less contaminated. So, it is better to assume that miners will use an escapeway next to the entry on fire (Fig. 4). Assume also some leakage from the entry containing the fire into the escapeway, typically through several stoppings. The aim here is to determine the visibility level along with the CO and oxygen concentrations in the escapeway.

Escapeway contaminant concentrations are calculated with a simple dilution equation. For example, if $Q_L$ is the leakage from fire airway to the escapeway and $Q_e$ the original amount of air flowing in the escapeway, then:

$$C_e = C_f\,(Q_L/Q_e+Q_L) \quad (2)$$

where $C_e$ is the concentration of contaminant in the escapeway and $C_f$ is the concentration of contaminant in the fire airway. For example, suppose $Q_e = 9.4$ $m^3$/sec (20,000 cfm). If one considers the fire at the 60 min point, $C_f$ for carbon monoxide from Fig. 1 is 2700 ppm. If the leakage $Q_L$ is 0.94 $m^3$/sec (2000 cfm), then $C_e = 245$ ppm.

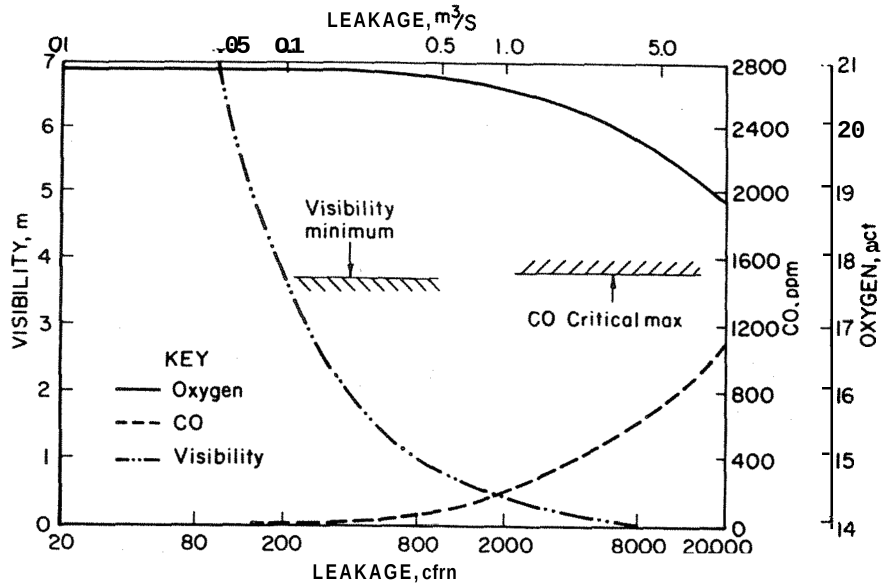


**Fig. 5—Calculated escapeway smoke visibility, oxygen and carbon monoxide vs. leakage—SBR belt/coal fire at 60 minutes.**

This simple dilution also applies to the smoke concentration expressed in optical density. For example, in the 60 min fire (OD = 29.3/m from Fig. 1) at 0.94 $m^3$/sec (2000 cfm) leakage:

Escapeway OD = Fire airway OD $(Q_L/Q_e+Q_L)$ = 29.3 (0.94/10.3) = 2.67/m.

Since visibility = 0.8/OD, then escapeway visibility = 0.812.67 = 0.3 m.

The escapeway oxygen percentage is calculated the same way by assuming the oxygen deficiency (AO,) is the contaminant.

Note that since the same formula is used for escapeway OD and CO, the ratio of CO to smoke OD is the same in both the escapeway and the fire airway. As a result, the data shown in Fig. 3 also apply to the escapeway.

### *Analysis of the adjacent escapeway data*

Using these dilution equations, escapeway concentrations were calculated as a function of leakage for the 60 min fire, which has an equivalent coal burning rate of 31 kg/min (67 lb per min). These escapeway concentrations are shown in Fig. 5, with smoke and CO critical values from Tewarson and Newman (1981).

The implications of these data for escaping miners and for fire protection are startling. For the 60 min fire, the smoke density reaches the visibility minimum at only 0.094 $m^3$/sec (200 cfm) of leakage. However, the CO concentration only approaches the critical maximum at leakages more than 9.4 $m^3$/sec (20,000 cfm). The escapeway oxygen level is adequate for the fire size and leakage range shown. With the critical values selected, the visibility drops below the acceptable minimum at a leakage rate less than 1% of the leakage producing the CO critical maximum. Smoke seriously hinders miners before the fire grows large enough to produce a carbon monoxide or oxygen deficiency problem.

These test results were obtained with combined SBR belt-coal fires. However, since the CO-to-smoke OD ratio for different burning materials varies within a limited range (see Table A-1 in the appendix), the authors believe that the same general results may apply to a wide variety of underground fires in their early growth stage. For example, coal fires alone give off similar amounts of smoke relative to their CO production. It could be argued that different critical values for smoke and CO should have been used. However, when any set of reasonable critical values for smoke or CO (Purser, 1988) are used, the general outcome is the same. Other information relating smoke to carbon monoxide is given in the appendix.

### Irritants in smoke

Sensory irritation from smoke may also hinder escape from coal mine fires. Therefore, some subjective observations of smoke cloud irritation were made during a conveyor belt test tire. In this test, 910 kg (2000 lbs) of coal and a 2.1-m (7-ft) length of belt burned. The CO concentration and subjective response to the smoke were noted:

| CO concentration | Reaction |
|---|---|
| up to 40 ppm | Mild discomfort. Breathing labored and eyes mildly irritated. |
| 80 ppm | Hard to breathe. Eyes stung. |
| 160 ppm | Very difficult to breathe. Severe eye irritation. Could barely see. |

It is significant that severe sensory irritation can take place at CO levels that do not represent an immediate carboxyhemoglobin danger. These results on sensory irritation generally confirm the work of Rasbash (1975) and Jin (1981), but are tentative. More research on smoke irritation from coal fires should be conducted.

### Conclusions

Smoke is a key factor in escape from mine fires. In particular, if a fire is in the early growth stage, escaping miners will meet with visibility problems before any other. The minimum acceptable smoke visibility is reached before the critical maximum carbon monoxide value. This means that methods to guide miners through dense smoke may contribute greatly to saving lives during mine fires. The low leakage quantities necessary for poor visibility indicate that intake airways can be as susceptible to smoke visibility problems as return airways.

The role of the self-contained self-rescuer in isolating the lungs from smoke cloud irritants is vital since unbreathable levels of irritants may be more common than oxygen deficiencies. Severe sensory irritation is possible at CO levels indicating a small fire or very low air leakage. This means that reliable eye protection is very important.♦

### Acknowledgment

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## Appendix — Other information relating smoke to carbon monoxide

### *Woodfires*

The findings relating smoke to CO in coal mine fires have some precedent. For wood fires in hard rock mines, Litton (1981) found that the "critical fire size" for CO is 36 times greater than that for smoke. "Critical fire size" was defined as the size of fire beyond which escape is either impossible or marginal.

### *Smolderingfires*

Many fires will smolder for a long time before breaking into flames. In general, a fire that is large enough to contaminate the adjacent airway has already passed from the smoldering to the flaming stage. Nevertheless, it is worthwhile to look at the ratio of smoke to CO for smoldering fires also. Litton (1989) gave some relative CO values for flaming and smoldering fires that are equivalent to a smoke optical density of 0.1/m (Table A-1). Depending on the material burning, the smoke-to-CO ratio is 1.6 to 13.8 times higher for a smoldering fire than it is for a flaming fire. In short, for a given CO level smoldering fires generate more smoke than flaming fires.

**Table A-1—Relative values of CO at a smoke sensor alarm level of 0.1/m OD**

| Fuel | ppm CO flaming | ppm CO smoldering |
|---|---|---|
| Wood | 11.1 | 7.1 |
| Coal | 3.4 | 1.8 |
| SBR belt | 3.7 | 0.5 |
| PVC belt | 8.3 | 0.6 |
| Neoprene belt | 6.3 | 1.4 |
| Transformer fluid | 1.5 | — |
| PVC brattice | — | 2.2 |

Note also from Table A-1 that the CO-to-smoke OD ratio varies within a limited range for different flaming materials.

### *Observations by mine rescue teamslthe CO hazard*

The levels of smoke and CO used to compile Figs. 1-5 are only from fires in the early growth stage.

During the later stages of fire growth, the available fuel or oxygen dips below the level necessary to sustain it. Then the fire begins to die out, and the smoke begins to dissipate. Smoke dissipates because there are loss mechanisms for smoke particles, such as sedimentation, which will lower smoke levels. This is not true for CO, which remains for much longer periods. For example, Kuchta et al. (1982) in full-scale studies of sealed coal mine fires saw CO levels increase from 300 ppm to 30,000 ppm four days after sealing, while the smoke level decreased by a factor of 10. Other data acquired by Litton (1981a) also show that in a sealed (or quiescent) mine, the smoke level not only decreases at the source of the fire that is dying out, but also as the distance from the fire source increases.

Since mine rescue teams are not in the mine during the early stages of a fire, they may see conditions different from those in Figs. 1 through 5. Discussions with individuals from these teams have indicated they see no fixed relationship between the smoke visibility and the CO concentration. Moreover, they have measured as much as 1500 ppm of CO without any smoke visibility problems.

Suppression of fires, such as with an automatic sprinkler system, may result in higher CO levels relative to the amount of smoke. One important conclusion to draw from this is that the miner cannot use good visibility as a guaranteed indicator of low CO levels.

The role of smoke in hindering escape has been emphasized here by pointing out that the smoke hazard arrives before the CO hazard. One should not, however, minimize the CO hazard from mine fires. The coal industry is well aware of the hazards presented by CO, which need no amplification here. ♦

# Coal handleability — Addressing the concerns of the electric utility industry

B.J. Arnold, C.D. Harrison and R.A. Lohnes

Abstract — *More than 544 Mt (600 million st) of coal are handled annually for use by this country's coal-fired power plants. Coal is transported in various ways: overland conveyors, railcars, trucks and barges. It can travel short distances or thousands of miles, picking up moisture, freezing or drying. When the coal is received at the power plant, environmental problems with fugitive dust and further handling problems can arise. To ensure that power plant availability is not jeopardized by coal handling problems, the Electric Power Research Institute's (EPRI) Coal Quality Development Center (CQDC) developed a research program aimed at addressing utility coal handling problems. The program has identified key areas, and is investigating the cost and cause of coal handling problems as well as the solutions to these problems. The ultimate goal of the program is to develop a "handleability index" that utilities can use in their coal specifications or hardware for a utility's sampling system to predict handleability and determine if a coal shipment should be accepted.*

## Introduction

A western utility commissioned a study to determine the effects of burning a deep-mined Utah coal in place of its current Powder River Basin coal. After addressing all coal quality parameters affecting boiler operations, the investigators concluded there was no apparent problem in changing coals. The utility then purchased enough coal for a 30-day test bum. The result was unexpected. Excessive moisture and fines in the Utah coal plugged bins and feeders, forcing the utility to end the test bum after only 10 days. The coal's handling characteristics had been taken for granted.

Utilities with coal-fired power plants face a complex job when specifying coals for their boilers. They must be concerned with such potential problems as slagging and fouling, emissions, ash handling and corrosion. In addition, they have to take handling characteristics into account. Coal handling problems — wet, sticky coal, plugged bunkers and frozen coal in railcars, trucks or barges — can force plant deratings or outages if the problems are severe. Most utilities, therefore, build redundancy into their coal handling systems. Extra plant feed conveyors, bunkers and pulverizers are common. This added expense is not the only cost associated with coal handling. It takes extra manpower to unplug bunkers or to repair pulverizers.

## An EPRI coal handling project

EPRI's (now CQ Inc.'s) Coal Quality Development Center (CQDC) in Homer City, PA, initiated a Coal Handleability Assessment project to help utilities determine the handling characteristics of coals. Its goal was to develop a handleability index or sampling system hardware that will allow utilities to establish handling specifications and to determine when a coal meets such specifications.

As the initial step in the project, EPRI hosted a coal handleability workshop in 1987 to involve utility coal buyers, design engineers, coal suppliers and power plant engineers in defining major coal handling problems and areas of needed research. The workshop featured papers on laboratory techniques to determine handling characteristics, bin design, freeze conditioning agents and dust control.

Following the presentations, a panel discussed coal handleability research needs. This discussion provided three major conclusions:

- There is no accepted industry understanding of the relationship among coal quality variables (size consist, moisture content, clay content) and their combined effects on handleability;
- A handleability index or combination of current testing methods would help coal companies, utility coal buyer and power plant operators to compare different coals and predict potential handling problems; and
- Utilities need power plant cost data related to coal handling to estimate the potential cost of using different coals in a given power plant.

CQDC investigators used these conclusions to develop a project plan for 1988 and to guide CQDC test work in future years. The 1988 plan included a literature survey, a search of North American Electric Reliability Council data on power plant availability related to coal handling and collection of handleability data from materials handling consultants. This paper reviews the findings of this work and discusses current and future plans for the project, including the testing of a variety of coals in order to develop a handleability index.

## Why coal handleability research?

In 1986, at an EPRI CQDC advisory committee meeting, the committee addressed coal handling as an area needing more research. To address this concern, the CQDC initiated a formal project, first evaluating areas where research was needed and then determining what research should be carried out. The committee members and also attendees at the first CQDC workshop were asked to rank several coal handling problems in order of severity. The results of this survey (Table 1) show that plugged bins, plugged feeders and hang-up in bins are the biggest problems. Several other problems were ranked near the middle of the survey: sticky coal in transport, dusty coal on conveyors, and dusty coal in stockpiles. The remaining problems — frozen coal in storage, spontaneous combustion and caving in storage — were ranked as the least severe problems.

In a 1987 survey, utilities were asked to estimate how much they spend on coal handling problems each year. There were very few answers to this question, but one estimate was $100,000 annually at one location. Since cost data was obviously lacking, one way to begin to estimate the cost impact of coal handling

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